Vertex Reconstruction for the Mu3e Experiment Using the General Triplet Track Fit

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1 MOTIVATION

Modern particle physics experiments require
- High-rate track fitting
- Precise track and vertex reconstruction

Challenge: Track fit must include
- Multiple scattering
- Hit position uncertainties
- Energy loss
- Magnetic field effects

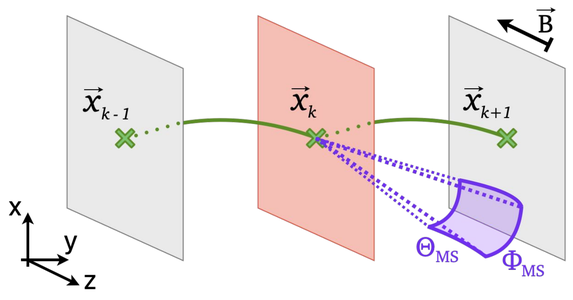
Current Standard: Kalman Filter
Extrapolates tracks and updates the vertex position iteratively: Highly successful but sequential.

Alternative:
Extension of the General Triplet Track Fit to include vertex reconstruction: Parallelizable

How precise is the GTTF vertex reconstruction?

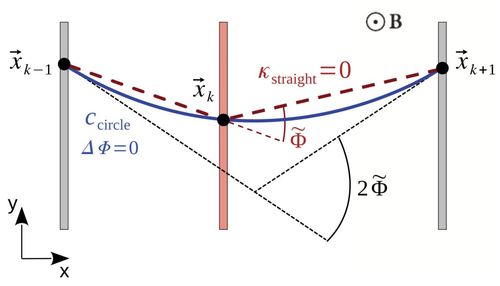
2 GENERAL TRIPLET TRACK FIT

The GTTF is an analytical track fit based on (overlapping) hit triplets.
- Includes **Multiple Scattering** and **Hit Uncertainties**
- The GTTF fits the particle momentum and hit positions while minimizing the
  - Multiple scattering angles Θ (polar) and ϕ (azimuthal)
  - Hit position shifts δ



$$\chi^2 = \underbrace{\sum_{j=0}^{n_{\text{scatt}}-1} \left(\frac{\Theta_{MS,j}^2}{\sigma_{\Theta_{MS},j}^2} + \frac{\Phi_{MS,j}^2}{\sigma_{\Phi_{MS},j}^2} \right)}_{\text{Multiple Scattering}} + \underbrace{\sum_{k=0}^{n_{\text{hit}}-1} \delta\vec{x}_k^{\,\top} \vec{V}_k^{-1} \delta\vec{x}_k}_{\text{Hit Uncertainty}}$$

Minimizing this χ^2 function leads to transcendental equations → Linearization needed



Linearization for a hit triplet between a zero kink angle solution and a zero curvature solution

3 VERTEX FIT USING THE GTTF

Advantages of a Vertex Fit Using the GTTF:
- Gives an **analytical solution** for the vertex position
- **Simultaneous fit** of the vertex position and the track parameters
- Triplet calculations are parallelizable

Method:
- Vertex position considered as a pseudo-hit for all tracks with a large position uncertainty
- Initial guess for the vertex position necessary
- χ^2 of the Vertex Fit: Fit of tracks (that include the vertex as a first "hit") with a common vertex shift

Vertex Fit χ^2

$$\chi^2_{\text{Vertex Fit}} = \sum_{i=1}^{N_{\text{tracks}}} \chi_i^2 + \underbrace{\vec{\delta}_{\text{vtx}}^{\,T} \mathrm{V}_{\text{vtx}} \vec{\delta}_{\text{vtx}}}_{\text{Contribution from the vertex}}$$

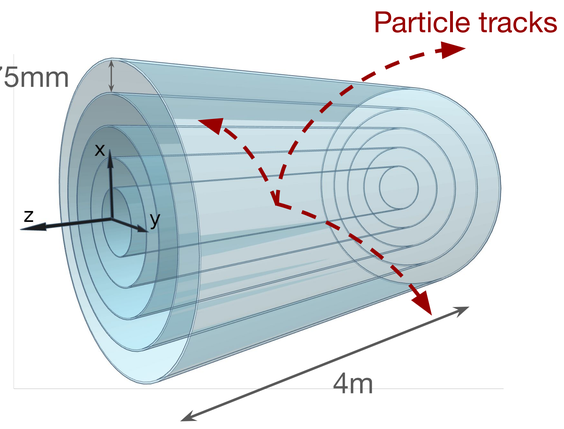
Contributions from the tracks

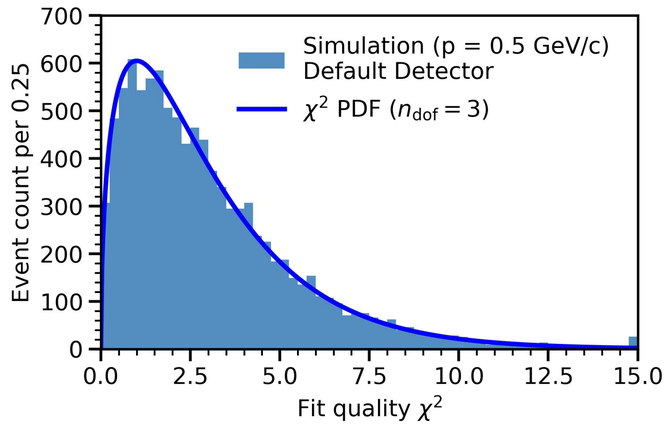
4 TOY DETECTOR VALIDATION

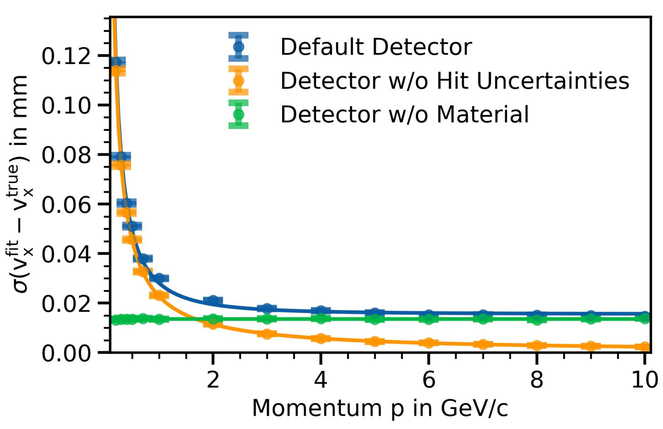
Simple detector geometry:
- 5 Barrel layers
- First layer: r = 40mm
- Uniform magnetic field with B = 1T in z-direction

	Material per Layer [X/X_0]	Sensor Size
Default Detector	0.002	[50 µm, 50 µm]
Detector w/o Hit Uncertainties	0.002	~ [0, 0]
Detector w/o Material	~ 0	[50 µm, 50 µm]

Simplified event generation:
- 3 particles/event at a common vertex
- fixed momentum for all particles







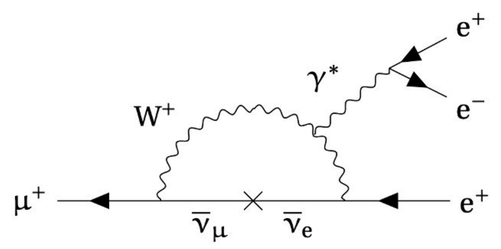
5 MU3E EXPERIMENT

Search for **charged lepton flavor violation** in the decay:

$$\mu^+ \rightarrow e^+ e^- e^+$$

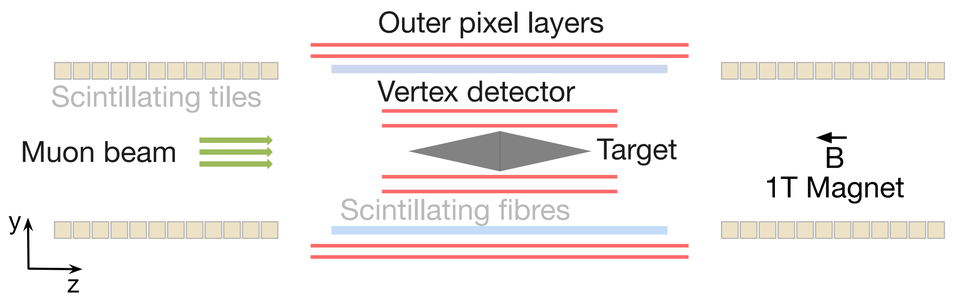
Standard Model prediction:
Only possible via neutrino mixing, therefore highly suppressed with

$$\mathrm{BR}(\mu^+ \rightarrow e^+ e^- e^+) \approx 10^{-54}$$

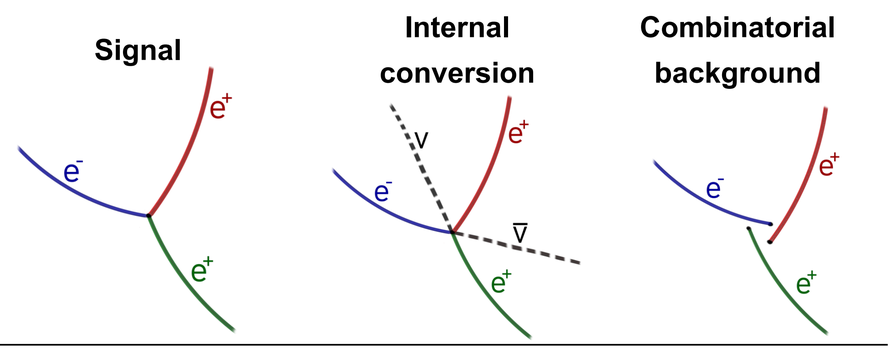


Muon decay via neutrino mixing

Phase 0 Mu3e Detector Design:
- Muon beam hits target → Muons are stopped → Muons decay in the target → Decay particles (electrons) leave hits in the detector
- **Speciality**: Particles can re-curl back into the detector
- Scintillating tiles and Scintillating fibres detectors are used for precise timing measurements



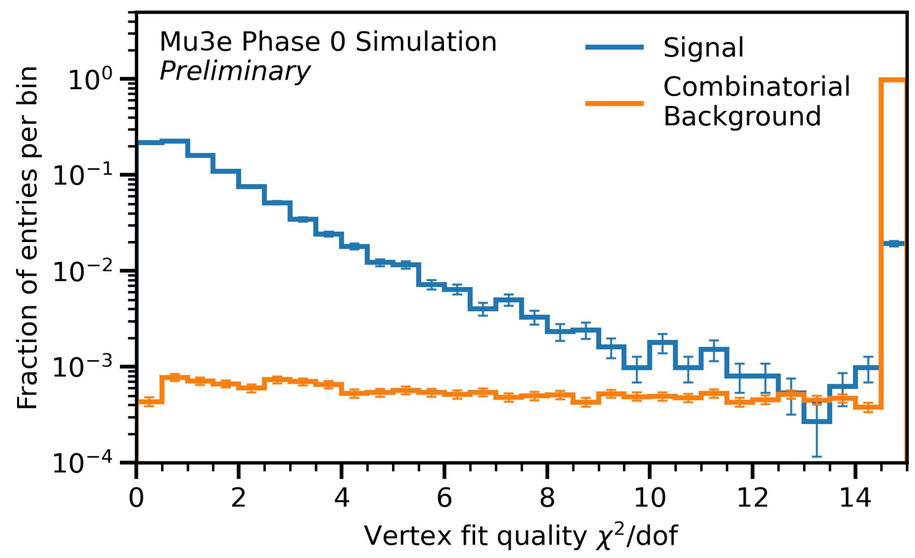
Experimental challenge: Distinguish signal decays from physics and combinatorial backgrounds



Common vertex	Common vertex	No common vertex
m_{eee} = Muon mass	m_{eee} < Muon mass	$m_{eee} \neq$ Muon mass
Total momentum = 0	Total momentum > 0	Total momentum > 0
Coincident in time	Coincident in time	Not coincident in time

6 RESULTS FOR MU3E

Mu3e Geant4 Simulation of Signal and Combinatorial Background:
- Common event cuts:
  - Re-curling tracks (minimum of six hits)
  - Correctly reconstructed tracks (Hits belong to the same Monte Carlo particle)



The GTTF Vertex Fit quality provides a strong discrimination power between signal and combinatorial background

TAKE AWAYS

The GTTF is a triplet-based track fit that includes multiple scattering and hit uncertainties

The GTTF can be extended to include vertex reconstruction

The behaviour of the vertex fit for a toy detector follows a theoretical model calculation

The Vertex Fit Using the GTTF can be used for the Mu3e Experiment